International Workshop on Wave Hindcasting and Forecasting/Coastal Hazards Symposium
Liverpool, UK, 10-15 September 2017

Open Ocean Storm Waves in the Arctic

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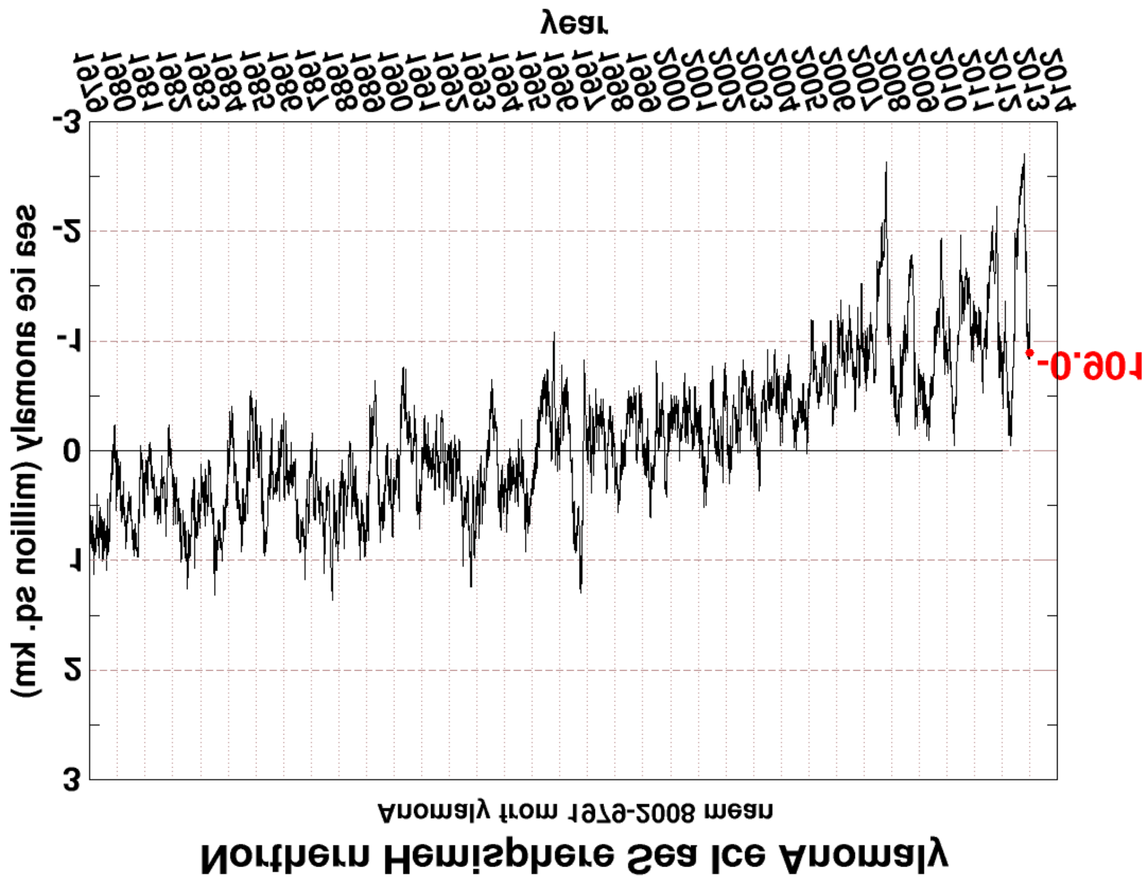
Arctic Challenge for Sustainability (ArCS) Program of the Japanese Ministry of Education, Culture, Sports, and Technology

Reduced Sea Ice Extent = Increased Area with Waves

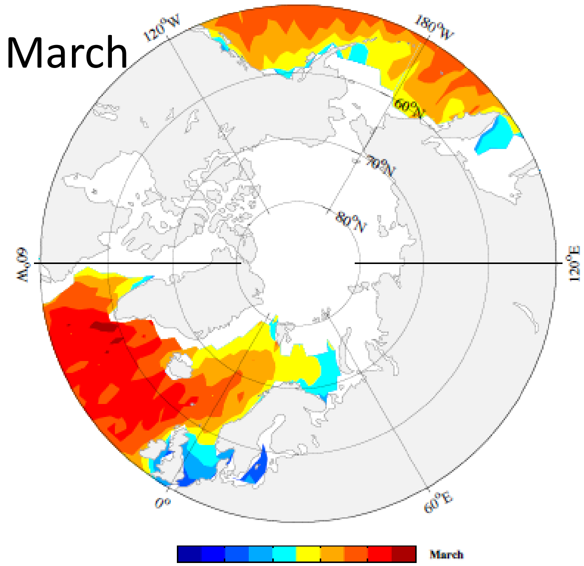


Walsh 2014

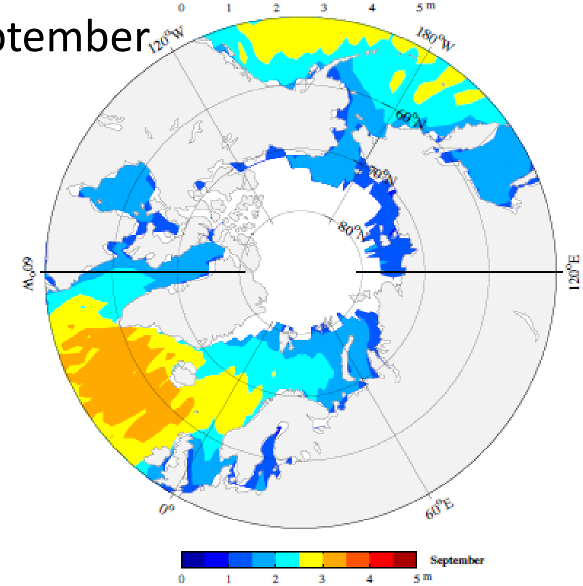
Wind waves are generated in the emerging ice-free waters as large as 1000 km x 1000 km

2002-2012 mean wave height

March



September



Babanin et al. 2014

Objective

To identify the long-term trend of the extreme wave height in the Arctic Ocean for the safe navigation of ships in the Northern Sea Route

Methods

- Drifting wave buoy measurements were conducted in 2016 Sep. to Nov.
- Validate numerical wave model in the ice-free and open waters
- The long-term trend was studied using the 38 year-long ERA-interim reanalysis (1979-2016)

Conclusion

Clear trend of the expected maximum significant wave height from the Laptev to Beaufort Seas was found. The cause of the increase is likely the increase of the expected maximum wind speed in the ice-free waters.

Waseda, Webb, Sato, Inoue, Kohout, Penrose and Penrose, 2017 under review

Maximum wave height in the ice-free waters

– estimating the trend of extreme values in changing wave climate –

- c.d.f. of the significant wave height

$$P(H_s)$$

- Probability of maximum Hs in N number of samples

$$1 - P({H_s}^{max}) = \frac{1}{N} \qquad N \equiv \#\ \text{of grids in ice}-\text{free waters}$$

- Maximum Hs in the ice-free waters (*areal maximum*)

$${H_s}^{max} = P^{-1}\left(1 - \frac{1}{N}\right)$$

- Assume Weibull distribution

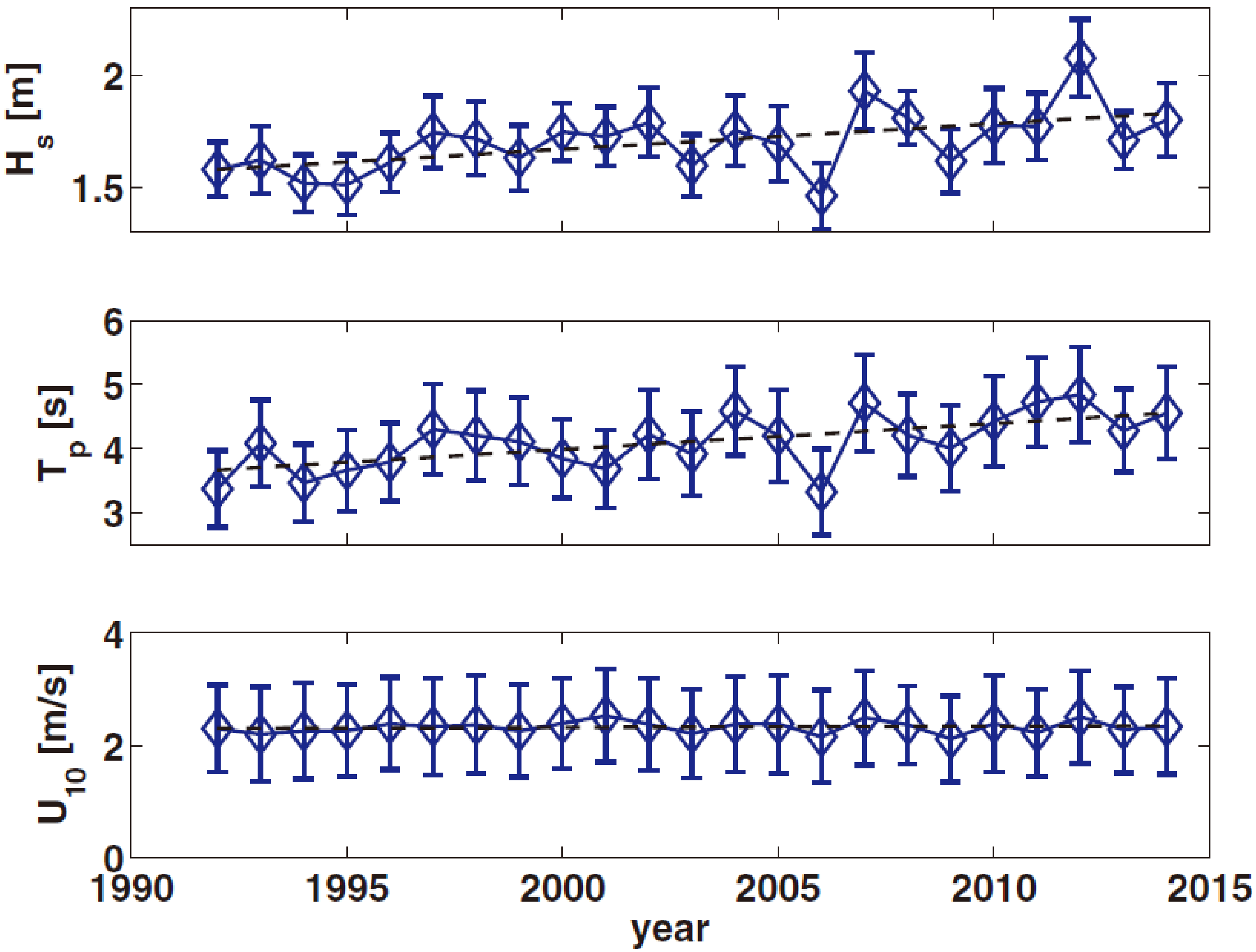
$$P(H_s) = 1 - e^{-(x/c)^k} \qquad \boxed{{H_s}^{max} = \mathrm{c}\ (\ln N)^{\frac{1}{k}}}$$

<u>*Outstanding Question*</u>:

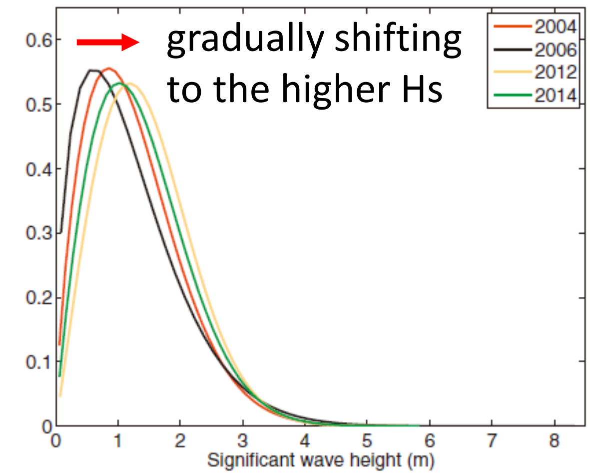
Which represents the trends in the Arctic Ocean, c or N?

Trend of Hs distribution（Beaufort & Chukchi sea）

Trend of the Weibull scale parameter c



Decadal trend of the pdf of significant wave height



p.d.f. $f(H_s) = \frac{k}{c}\left(\frac{x}{c}\right)^{k-1} e^{-(x/c)^k}$

c.d.f. $F(H_s) = 1 - e^{-(x/c)^k}$

Thomson et al. 2016

Fetch Law

Increased ice-free water distance → longer fetch → higher waves

$$H_s^{max} = c\,(\ln N)^{\frac{1}{k}}$$

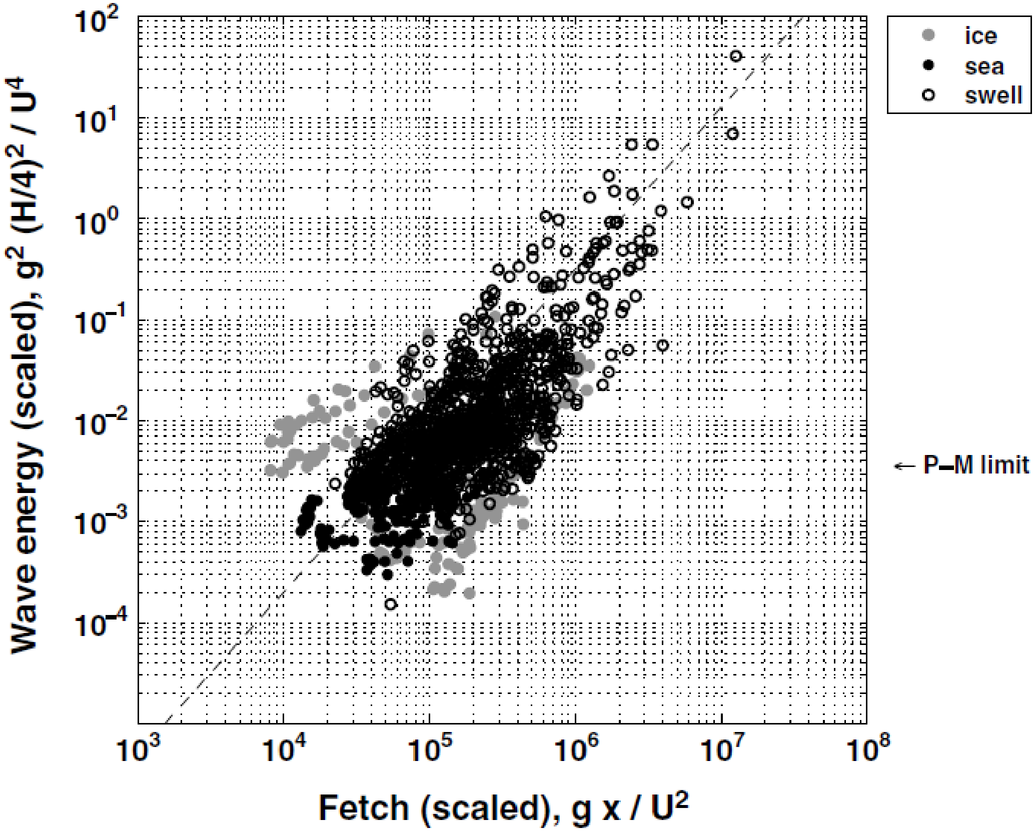


Figure 3. Scaling of waves in the Arctic Ocean, using nondimensional wave energy versus nondimensional fetch. There are 1880 points (each corresponding to an hourly observation from the in situ mooring at 75°N, 150°W). Symbols as in Figure 2. The dashed line is a regression with a logarithmic slope of 1.6. The Pierson–Moskowitz limit for pure wind seas is shown at $\mathcal{E} = 3.64 \times 10^{-3}$.

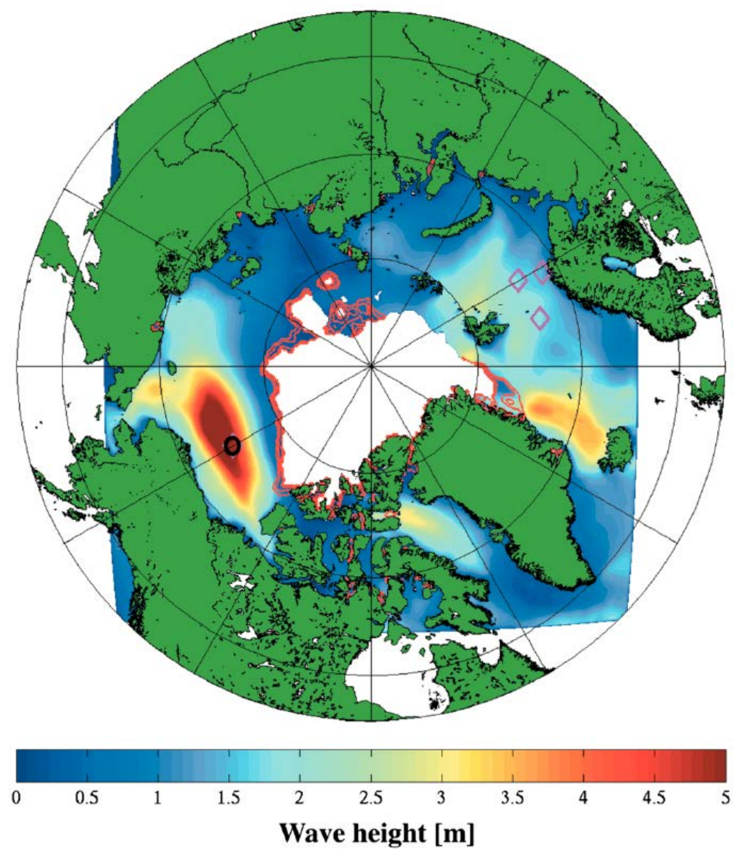


Figure 1. Example wave model hindcast during September 2012 storm. The map is centered on the North Pole, and the mooring location is indicated by the black circle north of Alaska. The color scale indicates significant wave height from 0 to 5 m.

Thomson & Rogers 2014 GRL

2016 summer wave observation

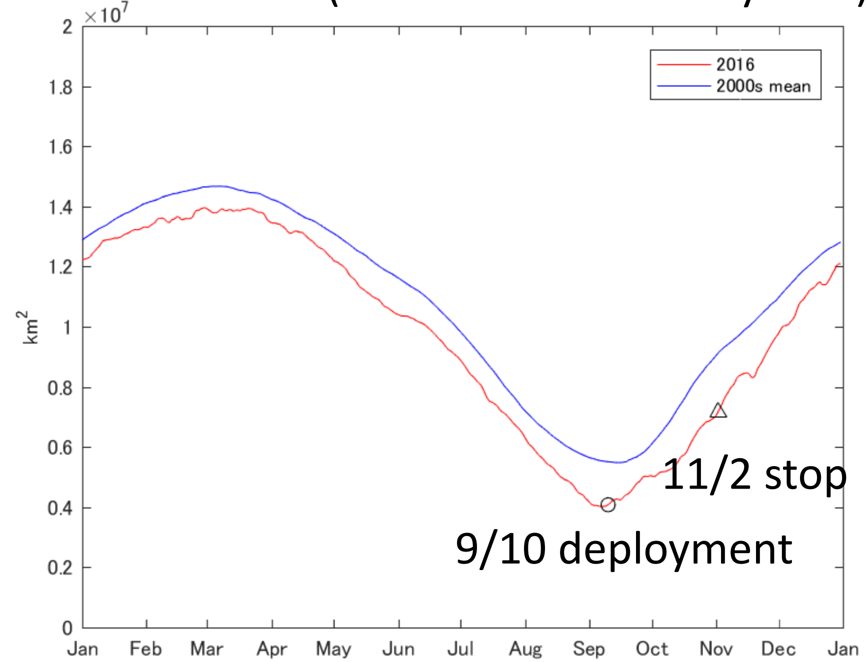
JAMSTEC MR16-06

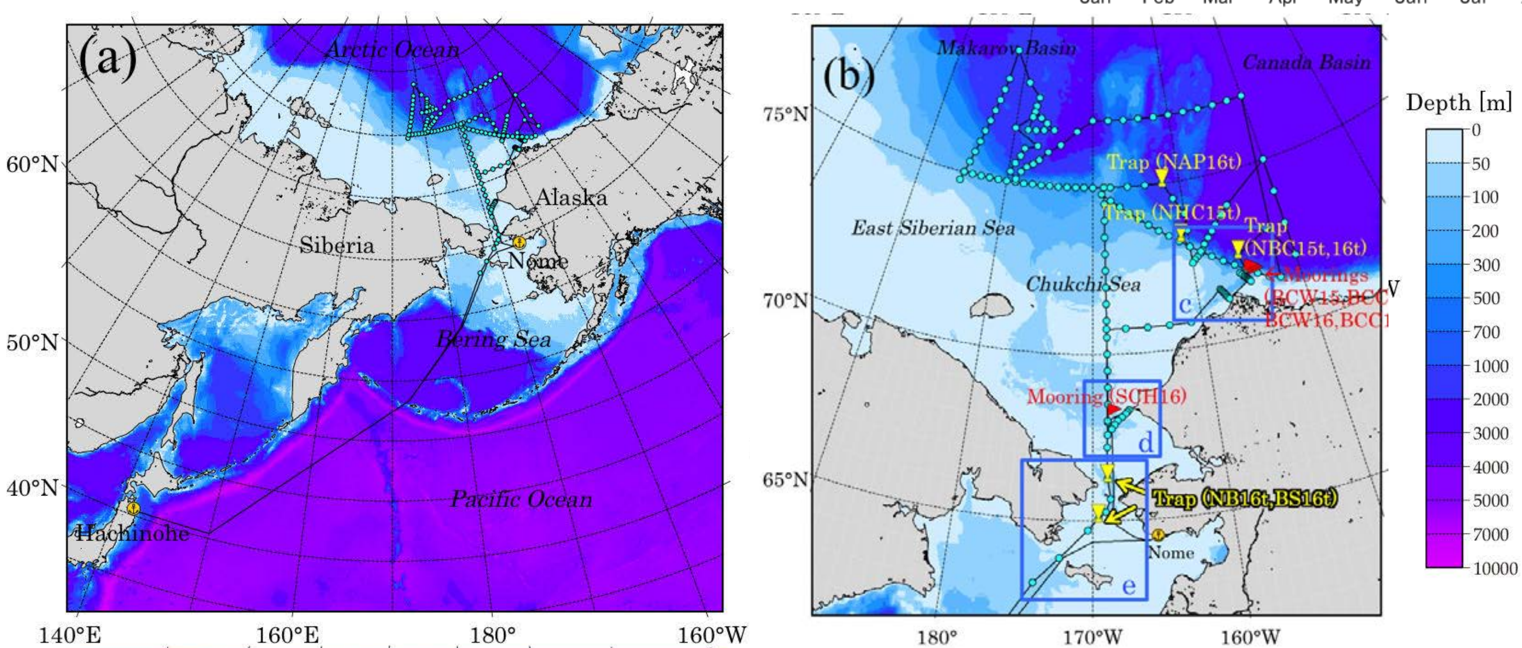
R. V. Mirai Cruise

2016 August 22 – October 5

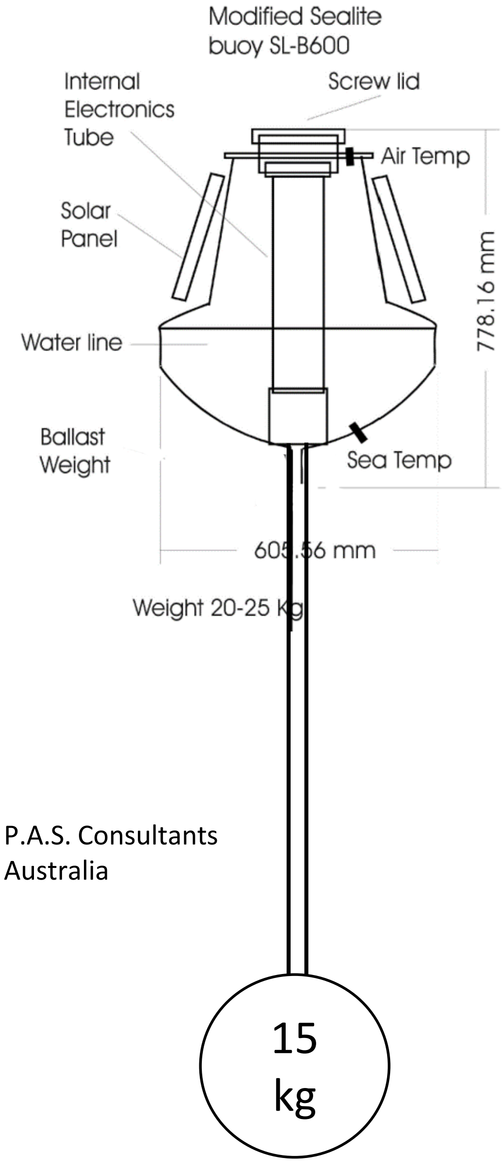
Wave Observation Sep.10 – Nov.2 2016

Arctic sea ice extent (Arctic Data archive System)





Waves In Ice (WII) buoy



P.A.S. Consultants
Australia

Specifications

Height without Keel - 778mm
Diameter - 606 mm
Weight without Keel - 20Kg
Weight with Long Keel -35Kg

Battery capacity 7.2V - 60 Amp Hour
Battery life without charging - 3 weeks at full load
3 External solar panels

3 temperature probes, air, sea and internal
GPS Receiver

Iridium SBD modem 9602

Intel Edison processor (includes WiFi)
9 degrees of freedom IMU MPU9250 (3-axis gyroscope, accelerometer and compass)

A device for measuring wave-induced motion of ice floes in the Antarctic marginal ice zone

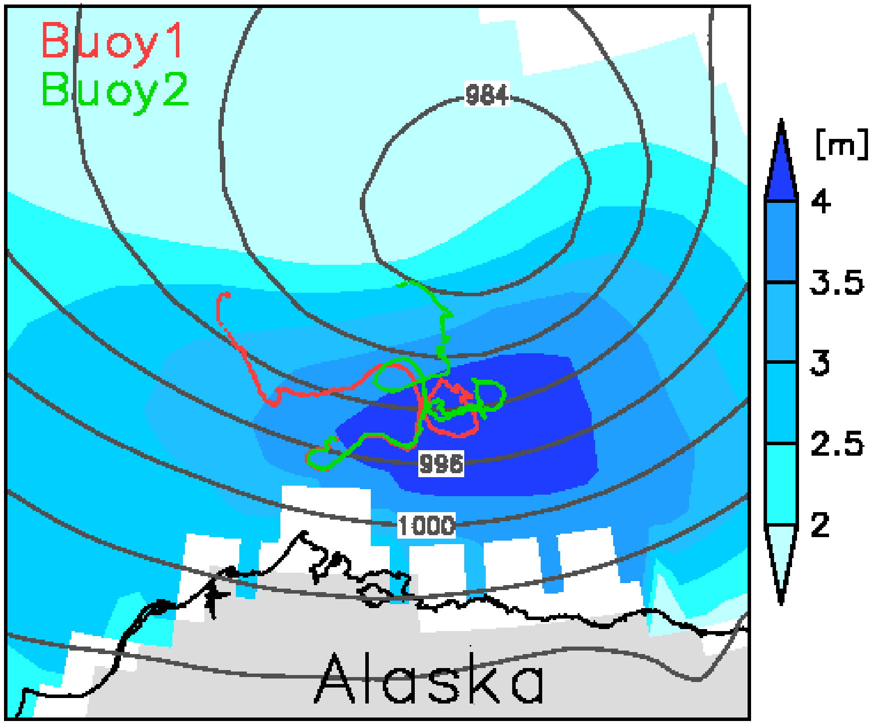
Alison L. KOHOUT,[1] Bill PENROSE,[2] Scott PENROSE,[2] Michael J.M. WILLIAMS[3]

Power spectral density
Spectral moments
Wave direction
etc.

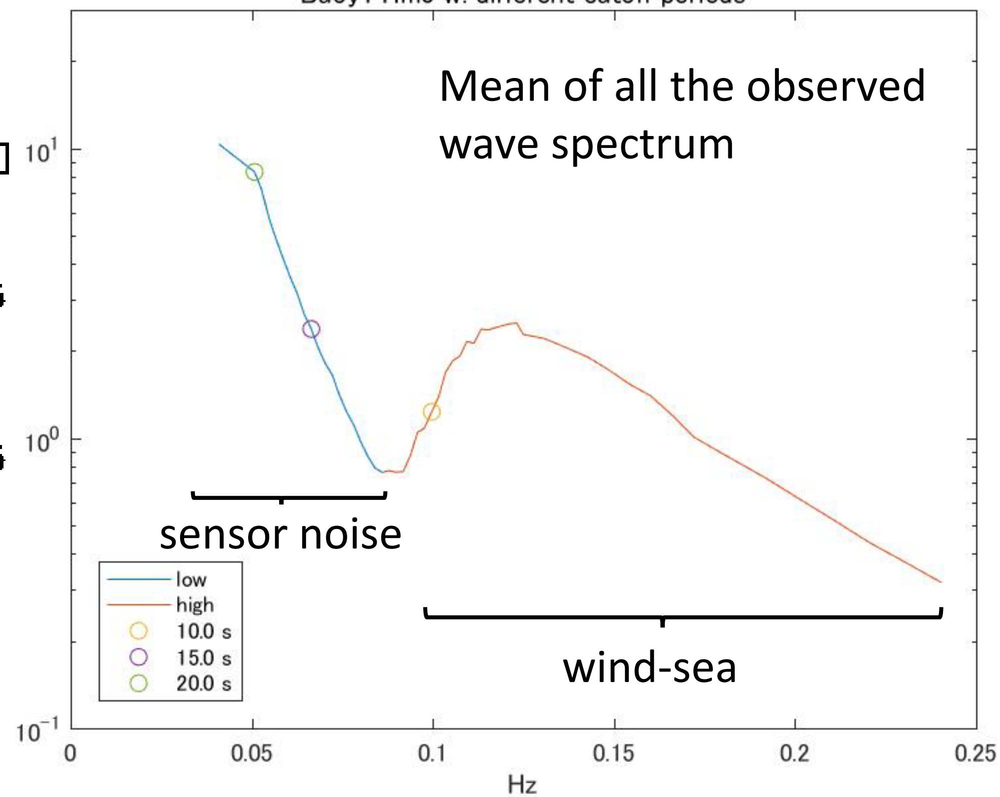
High-pass filter

Buoy Trajectories

SLP, SWH (00UTC19SEP2016) & Buoy tracks



Buoy1 Hm0 w. different cutoff periods



Buoy NO	Deployment		
	Date (YYYYMMDD)	Longitude (deg W)	Latitude (deg N)
1	10-Sep-2016 00:45:18 UTC	155.2819	72.6212
2	10-Sep-2016 01:45:32 UTC	155.3115	72.6219

Buoy NO	Lost conact		
	Date (YYYYMMDD)	Longitude (deg W)	Latitude (deg N)
1	02-Nov-2016 11:45:41 UTC	160.9832	74.3892
2	02-Nov-2016 18:45:19 UTC	152.4676	74.6402

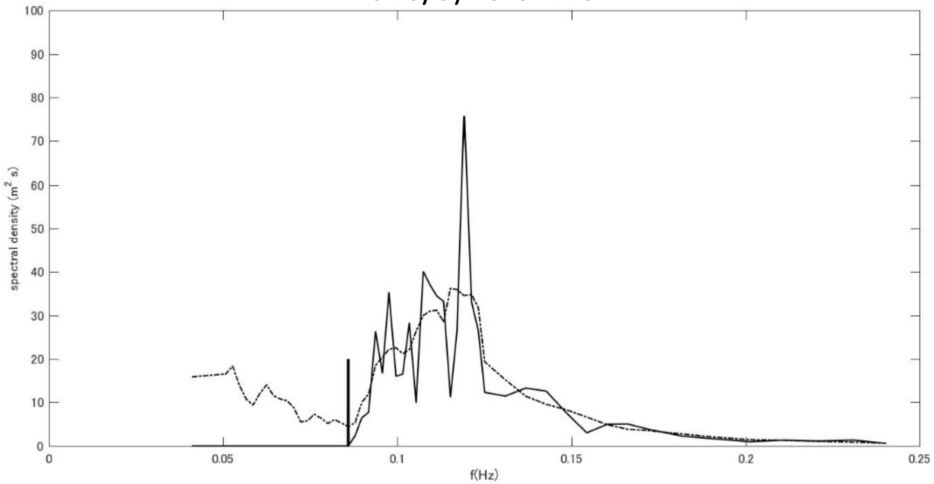
Default setting of the cut-off period was set to 33 s, which is too long for Arctic waves.

Post Processing: An adaptive filter was applied.

High-pass filter

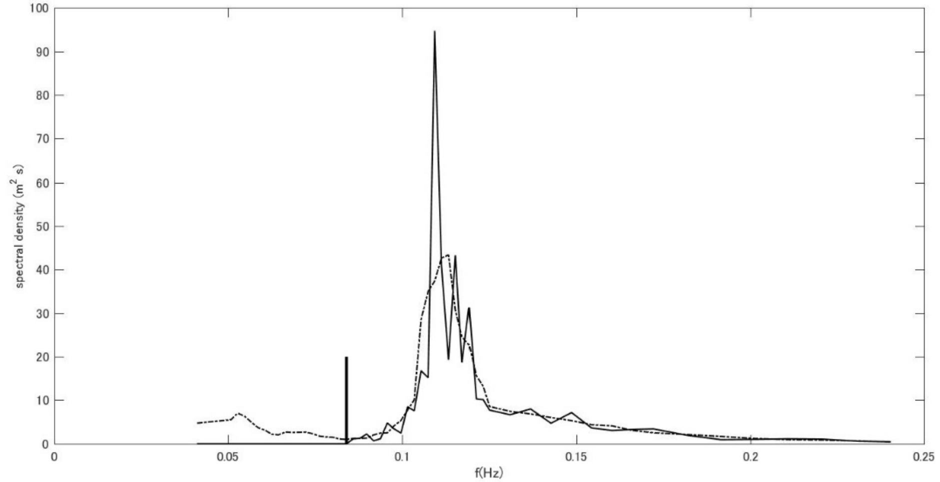
Spectra of the two observed extreme events

2016/9/19 07:46



Hm0=4.87

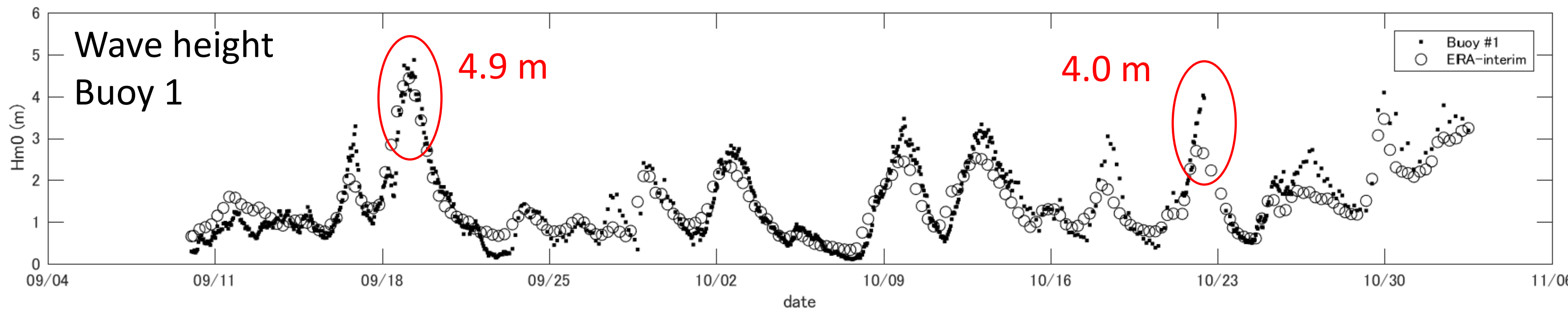
2016/10/22 09:45

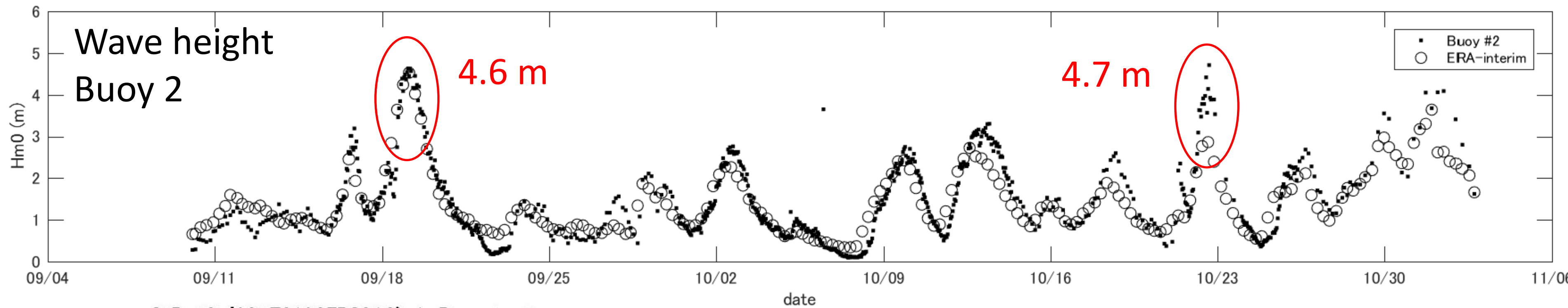


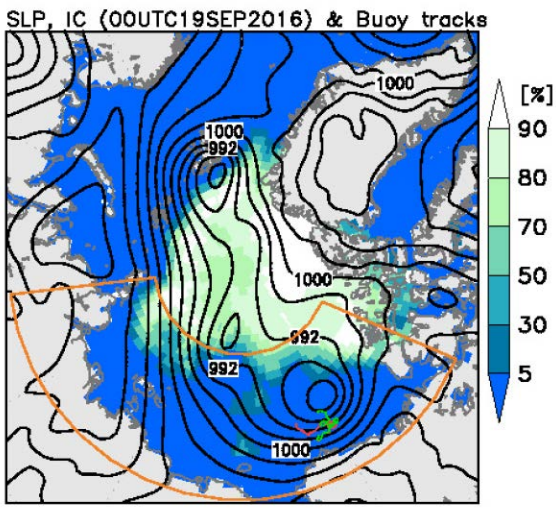
Hm0=4.02

- The cutoff frequency (fc) is determined from the minimum of the smoothed spectrum (dashed-dotted line).
- The total energy (m0) is determined from the original spectrum (solid line) applying an ideal high-pass filter at cutoff frequency fc (vertical solid line).

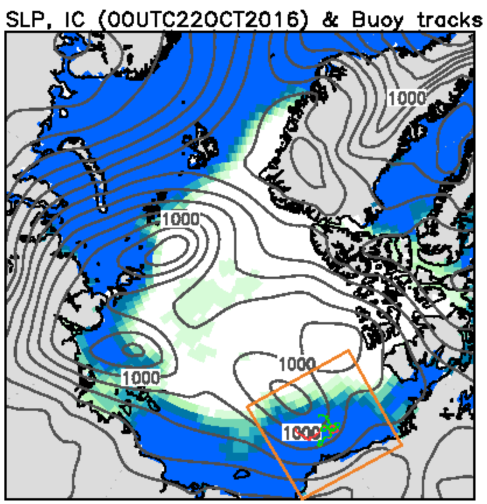
Observation vs. ERA-interim



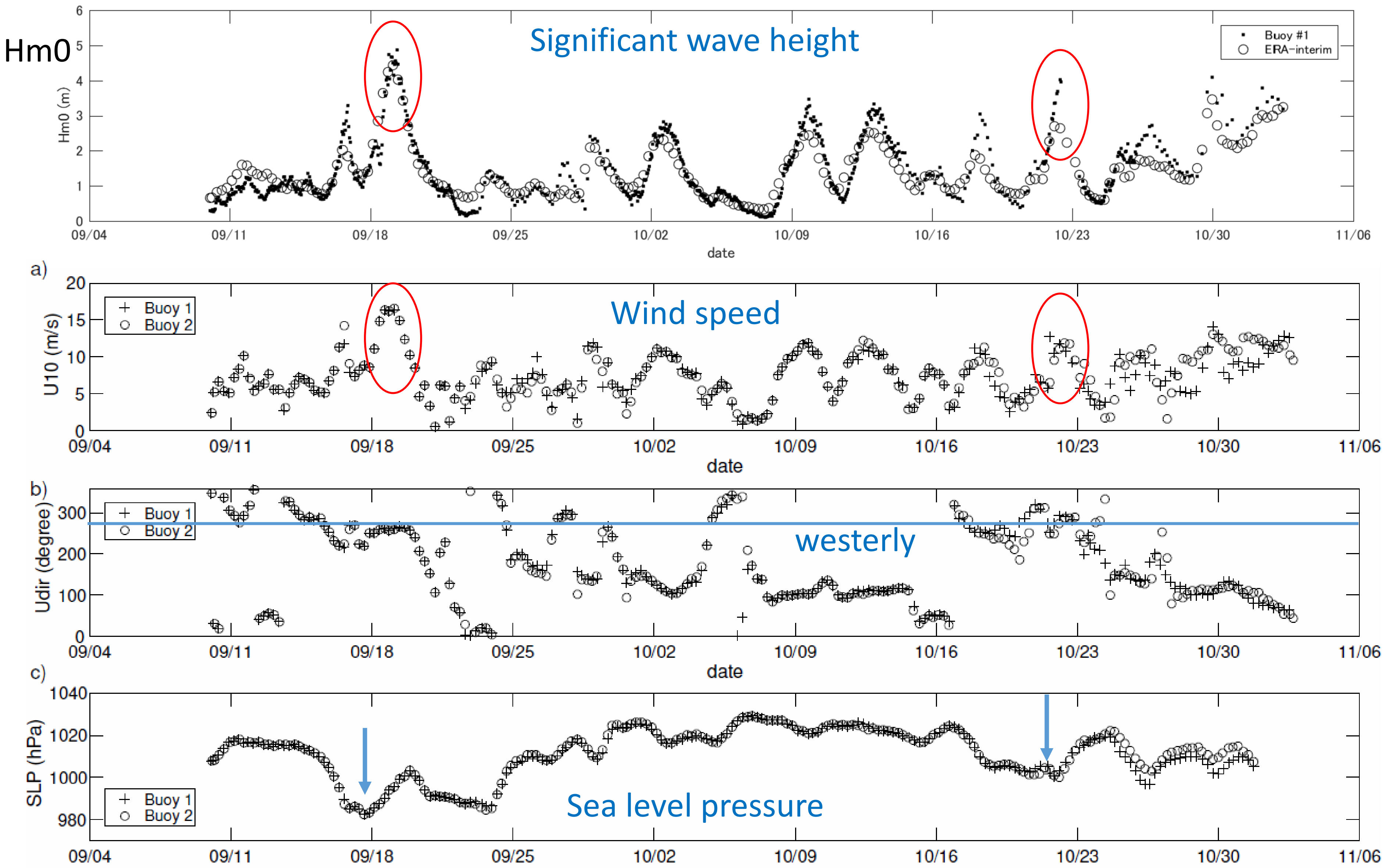




See: P67 “Ocean wave forecasting system for the Northern Sea Route” by Webb

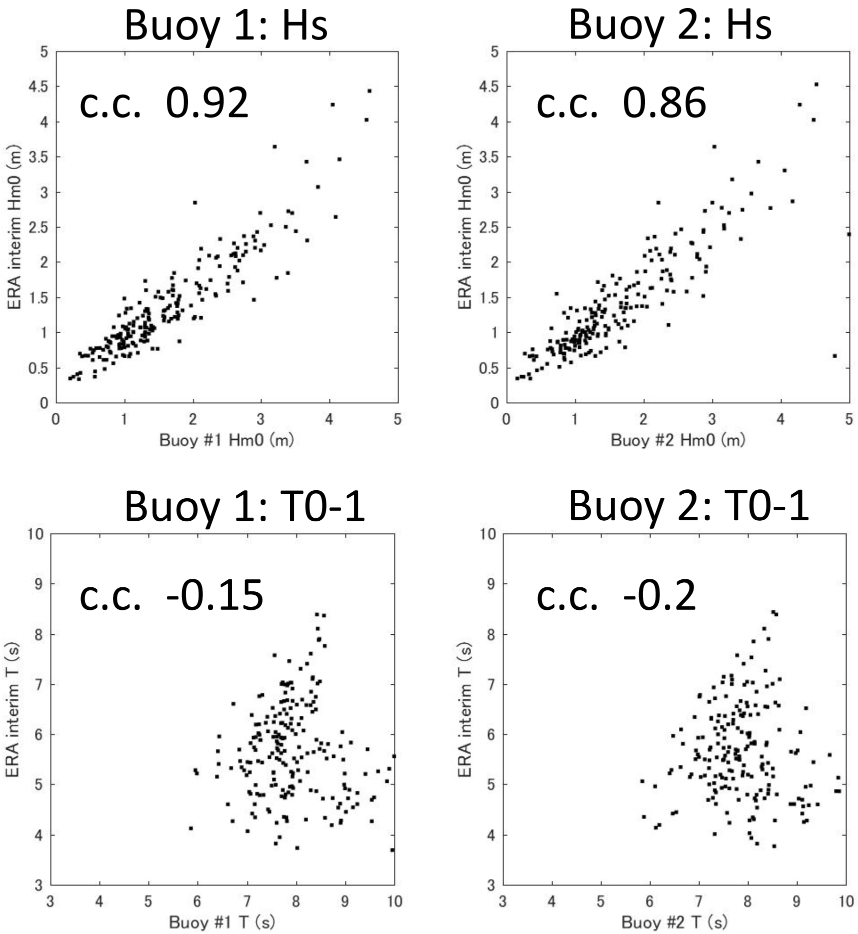


Wind field : depression associated w. extreme events

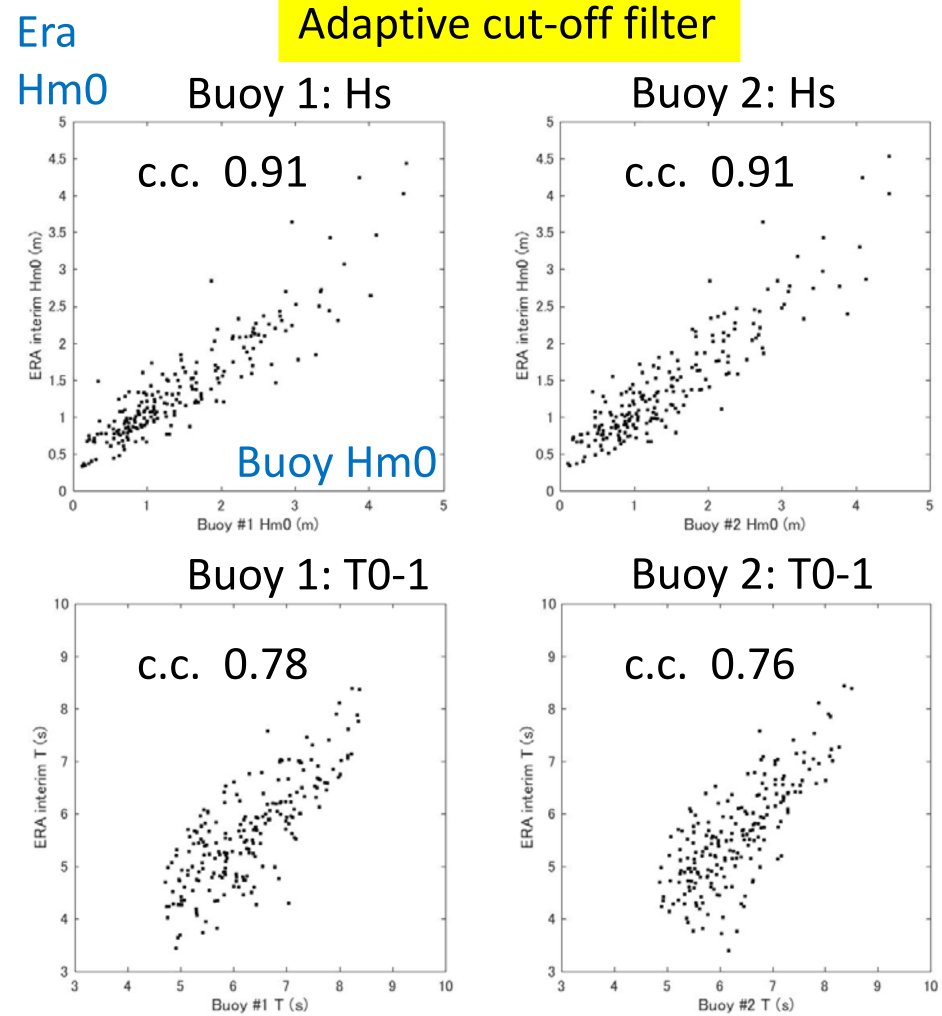


Post Processing: Comparison with ERA-interim

15 s cut-off filter



Adaptive cut-off filter



Significant improvement of the moment period with adaptive high-pass filter.

A similar c.c of Hs (0.91) was obtained w. the SWIFT buoy measurement in 2014 July-Sep

Long-term trend of the waves in the Laptev to Beaufort Seas

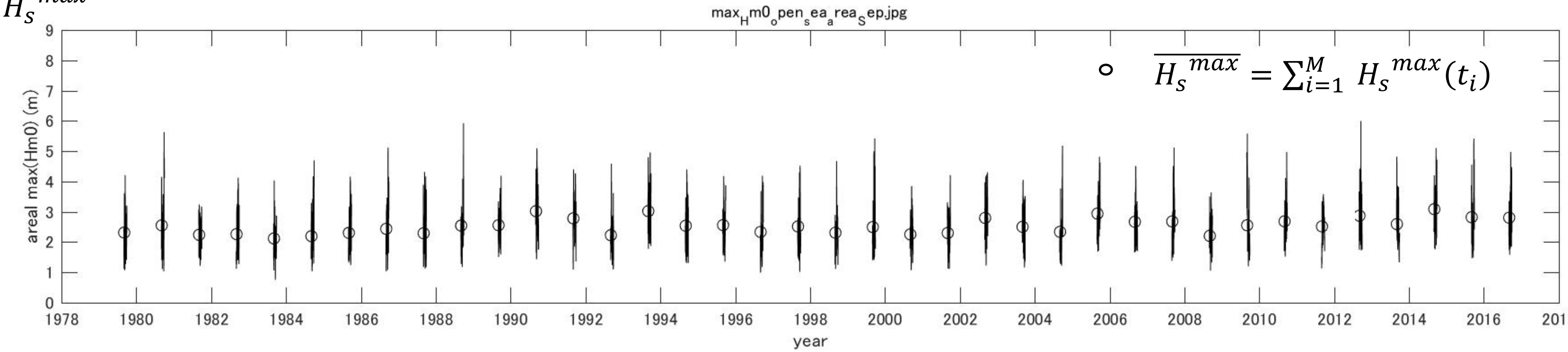
ECMWF: ERA-interim

1979-2016, 0.75 degrees resolution (30kmX110km), 6 hourly

September

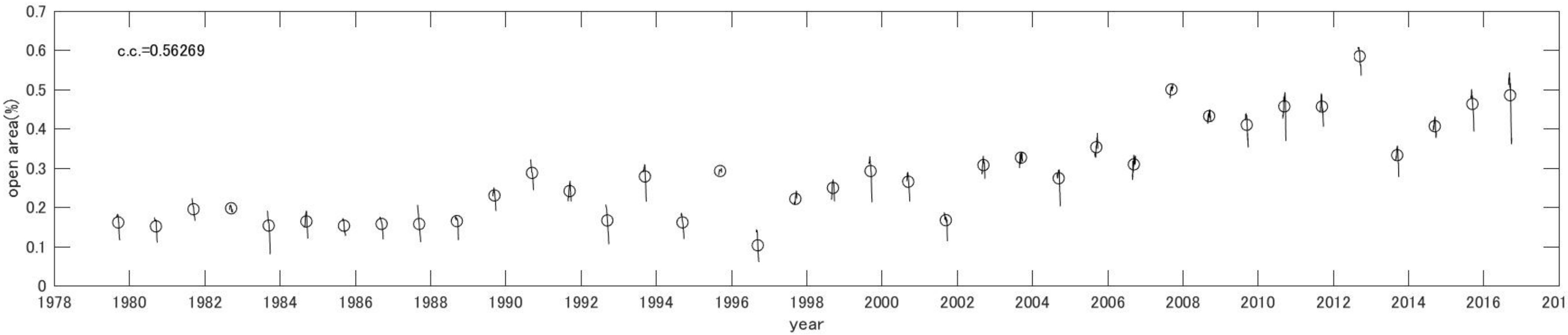
Maximum wave height in the Laptev to Beaufort Seas

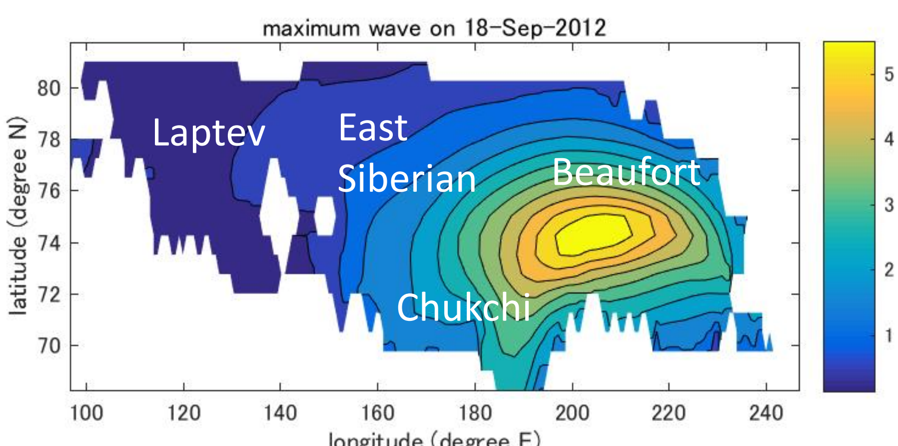
$H_s{}^{max}$



Percentage of ice-free and open waters (open area (%))

open area (%)





$$\text{open area (\%)} \equiv \frac{\text{\# of grids in open waters}}{\text{\# of grids in the analysis region}}$$

Analysis region: 96.75 E – 113.25 W, 68.25 N – 81.75 N

Estimating the *expected value* of the maximum wave height in the ice-free waters

For a given data set, the observed maximum significant wave height is itself a stochastic variable. The p.d.f. of the maximum wave height can be expressed as (c.f. Longuett-Higgins 1952)

$$f(H_s^{max}) = N\, P(H_s)^{N-1}\, p(H_s)\, dH_s$$

The expectation of H_s can readily be derived:

$$E[H_s^{max}] = \int_0^{\infty} [1 - P(H_s)^N]\, dH_s$$

The $E[H_s^{max}]$ will change with $P(H_s)$ and N.

The $E[H_s^{max}]$ is estimated in this study as following:

$$E[H_s^{max}] = \frac{1}{M} \sum_{i=1}^{M} H_s^{max}(t_i)$$

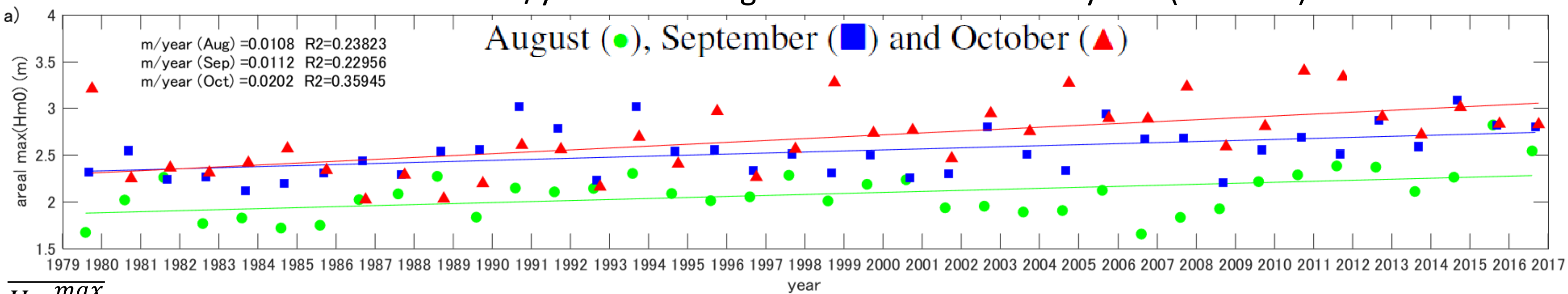
M: number of samples in a month

Extreme value in space, expectation as a time mean

Trends of the ERA-interim maximum wave & wind in Laptev to Beaufort Sea
There is a clear increasing trend for both wave and wind, rate is largest in October

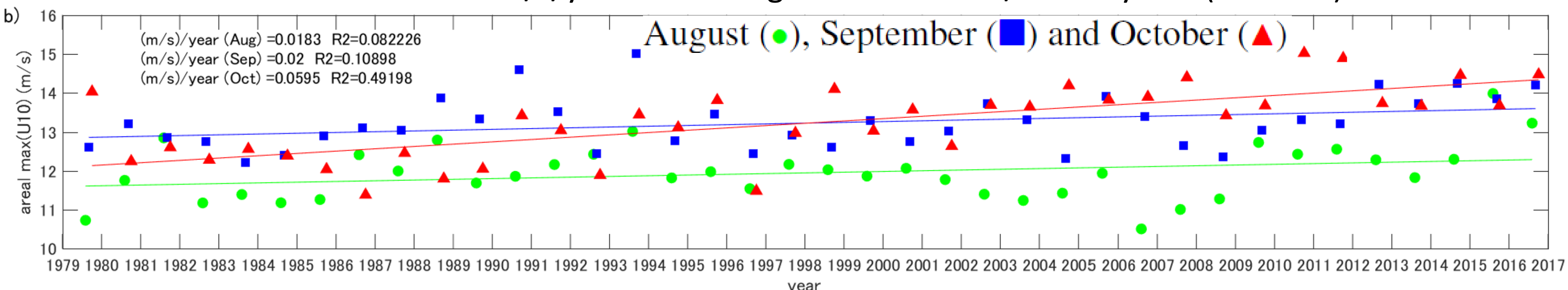
$\overline{H_s{}^{max}}$

1 to 2 cm/year increasing trend → 0.76 m in 38 years (October)

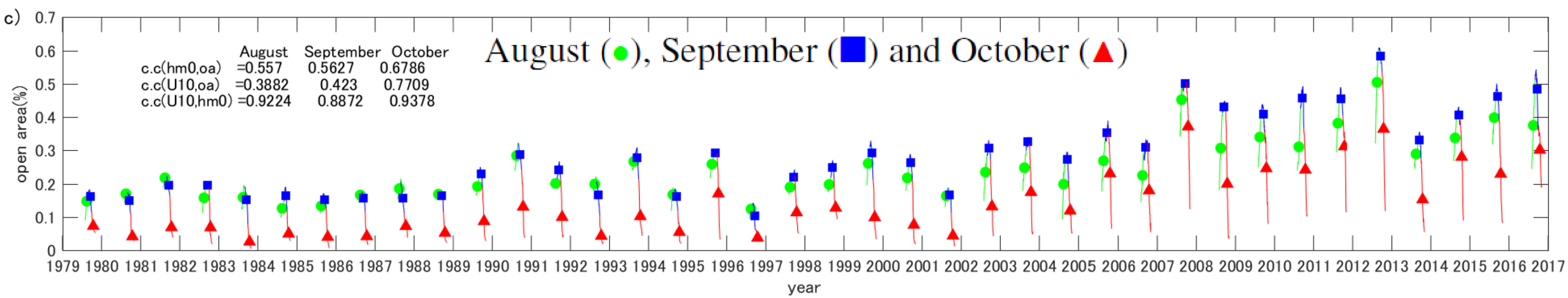


$\overline{U_{10}{}^{max}}$

2 to 6 cm/s/year increasing trend → 2.3 m/s in 38 years (October)



open area (%)



Partial correlation analysis : long-term and inter-annual variations

August (low)	$\langle \overline{H_s{}^{max}} \rangle$	$\langle \overline{U_{10}{}^{max}} \rangle$
$\langle \overline{\text{open area}} \rangle$	0.781	-0.687
$\langle \overline{H_s{}^{max}} \rangle$		0.947

August (high)	$\left(\overline{H_s{}^{max}}\right)'$	$\left(\overline{U_{10}{}^{max}}\right)'$
$\left(\overline{\text{open area}}\right)'$	0.077	-0.474
$\left(\overline{H_s{}^{max}}\right)'$		0.776

September (low)	$\langle \overline{H_s{}^{max}} \rangle$	$\langle \overline{U_{10}{}^{max}} \rangle$
$\langle \overline{\text{open area}} \rangle$	0.755	-0.554
$\langle \overline{H_s{}^{max}} \rangle$		0.921

September (high)	$\left(\overline{H_s{}^{max}}\right)'$	$\left(\overline{U_{10}{}^{max}}\right)'$
$\left(\overline{\text{open area}}\right)'$	-0.041	0.665
$\left(\overline{H_s{}^{max}}\right)'$		0.679

October (low)	$\langle \overline{H_s{}^{max}} \rangle$	$\langle \overline{U_{10}{}^{max}} \rangle$
$\langle \overline{\text{open area}} \rangle$	-0.65	0.845
$\langle \overline{H_s{}^{max}} \rangle$		0.947

October (high)	$\left(\overline{H_s{}^{max}}\right)'$	$\left(\overline{U_{10}{}^{max}}\right)'$
$\left(\overline{\text{open area}}\right)'$	-0.043	0.380
$\left(\overline{H_s{}^{max}}\right)'$		0.868

$$\overline{H_s{}^{max}} = \underbrace{\langle \overline{H_s{}^{max}} \rangle}_{low\ pass} + \underbrace{\left(\overline{H_s{}^{max}}\right)'}_{high\ pass}$$

$$\overline{U_{10}{}^{max}} = \underbrace{\langle \overline{U_{10}{}^{max}} \rangle}_{low\ pass} + \underbrace{\left(\overline{U_{10}{}^{max}}\right)'}_{high\ pass}$$

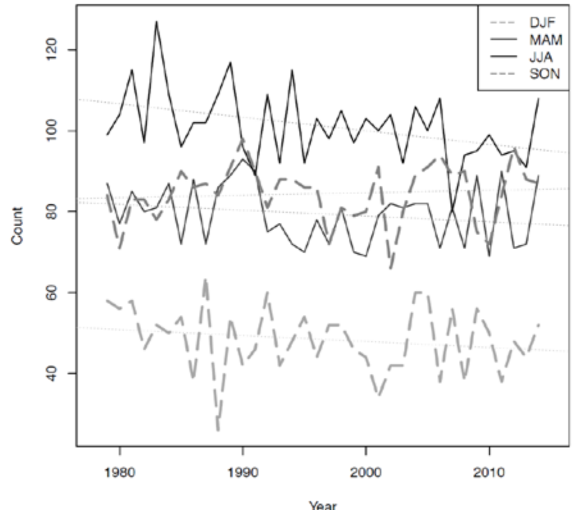
$$\overline{\text{open area}} = \underbrace{\langle \overline{\text{open area}} \rangle}_{low\ pass} + \underbrace{\left(\overline{\text{open area}}\right)'}_{high\ pass}$$

$\langle \quad \rangle$: 7 year moving point average

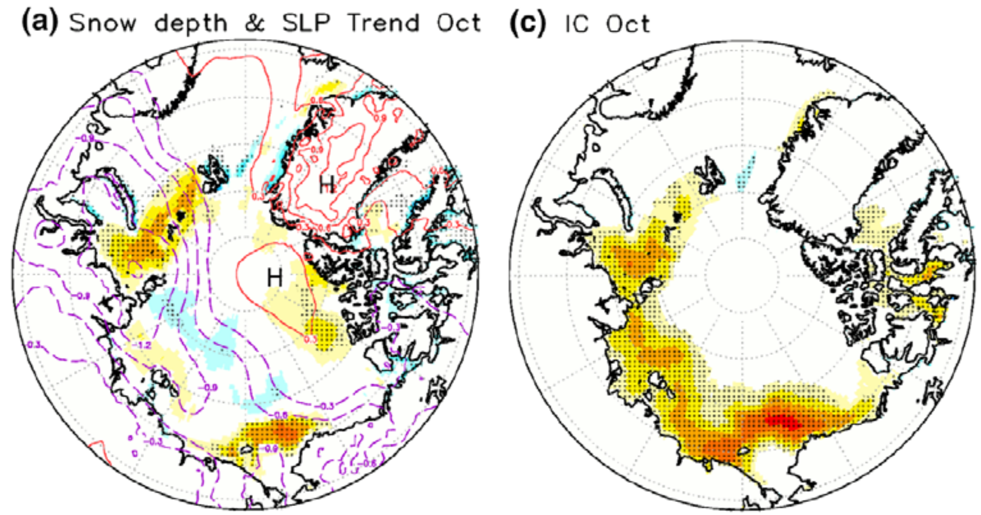
$$\boxed{\begin{aligned} H_s{}^{max} &= \mathrm{c}\ (\ln N)^{\frac{1}{k}} \\ U_{10}{}^{max} &= \mathrm{c}'\ (\ln N)^{\frac{1}{k'}} \end{aligned}}$$

- High p.c.c. between Hs and U10 implies that the trend can be explained by N, i.e. increase of the number of samples
- High p.c.c. between Hs and open.area implies that the trend can be explained by c, i.e. the fetch effect
- High p.c.c. between U10 and open.area needs physical explanation

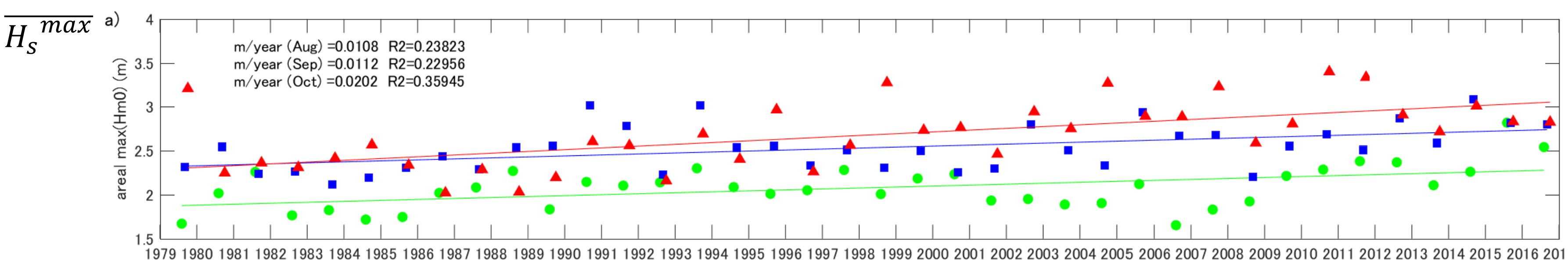
Long-term trends of storms in the Arctic



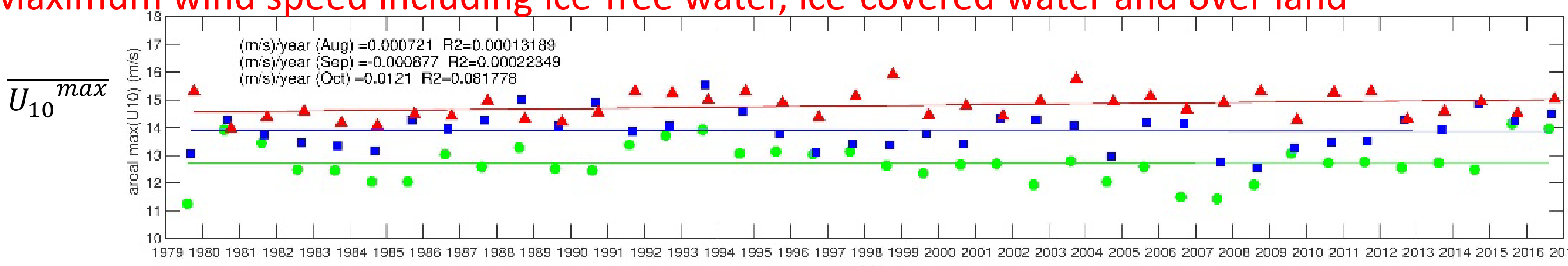
Koyama et al. 2017 J. Climate
No coherent trend in storm frequency



Sato & Inoue 2017 Clim Dyn
Weak SLP trend compared with the strong trend of ice concentration



Maximum wind speed including ice-free water, ice-covered water and over land



Conclusion

- WII buoy measurement was conducted in 2016 Sep. to Nov. in the Chukchi & Beaufort Seas

- ERA-interim wave field was validated by the observation and was used to study the long-term trend of waves in the ice-free waters in the Arctic Ocean

- The wind in the Arctic region is not strengthening but the wind in the ice-free water is strengthening.

- It is conjectured that the expected maximum wave height increased in the past 38 years, because, the chances of encountering a strong wind in the ice-free water is increasing.

Trend in the mean & scale parameter (Weibull)

Trends	mean H_s (m/year)	c_{H_s} (m/year)	mean U_{10} (m/s/year)
August	0.004 (R2=0.17)	0.0039 (R2=0.14)	-0.0015 (R2=0.0017)
September	0.0051 (R2=0.23)	0.0060 (R2=0.24)	-0.0031 (R2=-0.003)
October	0.0054 (R2=0.12)	0.0049 (R2=0.049)	0.0045 (R2=0.013)

Table 2. Linear trends of the maximum values of H_s and U_{10}

Trends	max of H_s (m/year)	increase over 38 years	max of U_{10} (m/s/year)	increase over 38 years
August	0.0108 (R2=0.24)	0.41 m	0.0183 (R2=0.082)	0.70 m/s
September	0.0112 (R2=0.23)	0.43 m	0.0200 (R2=0.11)	0.76 m/s
October	0.0202 (R2=0.36)	0.77 m	0.0595 (R2=0.49)	2.26 m/s

Expected value of the maximum significant wave height

Let $P(H_s)$ be the cumulative distribution function of the significant wave height H_s,

$$P(H_s) = \int_0^{H_s} p(H_s) dH_s, \tag{8}$$

where $p(H_s)$ is the p.d.f. of the significant wave height H_s. For N observational or grid points of a numerical wave model in ice-free waters, the largest significant wave height among these is

$$1 - P(H_s^{max}) = \frac{1}{N}. \tag{9}$$

Assuming further that the p.d.f. can be approximated by a Weibull distribution $P(H_s) = \exp\left\{-\left(\frac{H_s}{c_{H_s}}\right)^k\right\}$, the maximum significant wave height reads

$$H_s^{max} = c_{H_s} (\ln N)^{\frac{1}{k}}, \tag{10}$$

which is valid for a large value of N[5]. This simple relationship indicates that the largest H_s in ice-free waters is related to the distribution of H_s, the scale parameter c_{H_s}, and the extent of the ice-free waters as represented by N.

For a given number of N, the observed H_s^{max} is itself a stochastic variable. Therefore, the most likely values of H_s^{max} can be derived as follows. First, consider the probability that the significant wave height exceeds H_s at one observational point, or at one grid point, $1 - P(H_s)^N$. Following Longuet-Higgins[15], the probability that the maximum value of the significant wave height lies within H_s and $H_s + dH_s$ is $dP(H_s)^N = NP(H_s)^{N-1}\, p(H_s)\, dH_s$, and thereby, the p.d.f. of the H_s^{max} is given as

$$f(H_s^{max}) = N\, P\,(H_s)^{N-1}\, p(H_s)\, dH_s. \tag{11}$$

If the cumulative distribution function P or the p.d.f p of H_s is known, the median, mode and mean of H_s^{max} can be readily derived from f. In particular, the expectation or the mean of the H_s^{max} can be expressed as

$$E\,[H_s^{max}] = \int_0^{\infty} \left[1 - P\,(H_s)^N\right] dH_s. \tag{12}$$